Thermosphere-Ionosphere-Mesosphere Modeling Using the TIME-GCM

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LONG TERM GOAL

A major goal of the research is to understand how elements in the coupled upper atmosphere/ ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the variable input from the lower atmosphere and ocean. The research focuses on understanding the sources and characteristics of global-scale ionospheric, thermospheric, and mesospheric structure and variability and the coupling of those atmospheric regions to the lower atmosphere and to the magnetosphere and solar wind.

SCIENTIFIC OBJECTIVES

I wish to understand the nature of the sources of variability in the upper atmosphere/ionosphere system and how they are related to solar radiative and auroral particle and electric field forcings. I am also interested in understanding how disturbances from the lower atmosphere and ocean affect the upper atmosphere and how this variability interacts with the variability generated by solar and auroral sources. We accomplish this task by developing large-scale numerical models of the upper atmosphere and ionosphere and using these models to analyze data obtained by satellites and ground-based observatories as well as using these models for numerical simulations to understand how upper atmosphere/ionosphere physics and chemistry interact.

APPROACH

A hierarchy of numerical models has been developed that describes the upper atmosphere and ionosphere and these models have been used to study atmosphere/ionosphere interactions and their response to solar and auroral variability for nearly 20 years. The current version of models include: the TIE-GCM, TIME-GCM, and flux-coupled TIME-GCM/CCM3, where the I, M, and E represent “ionosphere,” “mesosphere,” and “electrodynamics,” respectively. The CCM3 is the NCAR Community Climate Model, Version 3.6, a GCM of the troposphere and stratosphere. All models include self-consistent ionospheric electrodynamics, that is, a calculation of the electric fields and currents generated by the ionospheric dynamo, and consideration of their effects on the neutral dynamics. The TIE-GCM is used for studies that focus on the thermosphere and its coupling with the ionosphere and magnetosphere. The TIME-GCM, the most elaborate of the upper-atmospheric TGCMs, solves for global distributions of neutral and plasma temperatures, velocities, and compositions, including all of the species that are photochemically important in the mesosphere, thermosphere, and ionosphere. The flux-

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coupled TIME-GCM/CCM3 is a climate model that extends from the ground, including oceans, to 500 km altitude to study global atmospheric variability and couplings.

In addition to the above models we also use the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) to provide auroral inputs and a Global Scale Wave Model (GSWM) to study tides and planetary wave propagation in the atmosphere. The latter is a linearized model that is useful in helping understand tidal and wave phenomena in the non-linear TGCM's.

NCAR personnel participating in this work include: Raymond G. Roble (aeronomy and global upper atmosphere and ionospheric dynamics), Arthur D. Richmond (electrodynamics and upper atmosphere waves), Hanli Liu (gravity wave parameterizations), Barbara A. Emery and Gang Lu (campaign studies and data analysis), and Benjamin Foster (programming support and model development).

WORK COMPLETED

- Major improvements were made to the aeronomical scheme in both the TIE-GCM and the TIME-GCM. Based on comparisons between satellite data and model predictions it was necessary to increase the solar X-ray flux to increase E-region electron density for dynamo calculations and to increase NO densities in the lower thermosphere. Changes were made to certain F-region ion chemical reaction rates and a calculation of nitrogen vibration temperature was included in both the TIE-GCM and TIME-GCM. A new solar flux model based on a recent re-analysis of satellite data was also included.

- A new gravity wave parameterization similar to the one used in the NCAR Community Climate Model (CCM3) was introduced into the TIME-GCM and numerous tests were made. The parameterization allowed for enhanced gravity wave forcing over mountainous regions and it was found necessary to increase the eastward forcing of waves in order to best match climatology. Considerable tuning was also made to the calculated eddy diffusion so that the calculated upper atmosphere compositional structure was in reasonable agreement with satellite data.

- Numerous airglow emission lines were introduced into the TIME-GCM post processors in order to calculate emissions along the satellite track for comparison with upcoming NRL satellite data. The g-factors for these emission lines were obtained from Douglas Strickland (Computational Physics Inc.) and incorporated into the processor and tested.

- In order to better understand electrodynamic couplings between the magnetosphere and ionosphere we have coupled the TIE-GCM with a model of the inner magnetosphere. This new model is called the Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation Model (MTIE-GCM).

- A new spectral analysis procedure has been developed to examine the waves and non-linear wave-wave coupling in the TIME-GCM. The analysis routine calculates stationary and traveling components and describes the interaction between waves and the mean flow. This diagnostic package provides considerable insight into physical processes operating in the non-linear TGCM's.

RESULTS

The results from some of the studies conducted during the past year include the following:

- A new simulation model of the thermosphere, the ionosphere, and the magnetosphere was developed by Christophe Peymirat (University of Versailles), Arthur Richmond (HAO), Barbara Emery (HAO), and Raymond Roble (HAO). This model, called the Magnetosphere-Thermosphere-Ionosphere Electrodynamics General Circulation Model (MTIE-GCM), calculates the three-dimensional structure of the thermosphere and the ionosphere, the two-dimensional magnetospheric plasma convection in the equatorial plane of the magnetosphere, and the couplings among the thermosphere, the ionosphere, and the magnetosphere. The electrodynamic couplings induced by the auroral precipitation, the region~2 field-aligned currents, and the neutral winds are self-consistently computed. The MTIE-GCM was run for solar maximum conditions and moderate magnetic activity in a sample case, where the electric potential was imposed in the polar cap but calculated everywhere else, to study the electrodynamic couplings occurring at high latitudes. The neutral winds were found to increase the north-south component and decrease the east-west component of the ionospheric electric field, corresponding to an enhancement of the shielding effect by 10%. The region~2 field-aligned currents and the distribution of the magnetospheric pressure showed smaller modifications, suggesting that the magnetosphere acts partly as a current generator. It was pointed out that the results could possibly be different if the polar cap electric potential were allowed to change due to the neutral winds.

- Robert Stening (University of New South Wales), Richmond, and Roble studied the ionospheric effects of lunar semidiurnal tides with the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model. The tides at the lower boundary were derived from the model of Vial and Forbes and interesting properties of these tides were found when they were subjected to Hough decomposition: there is considerable hemispherical antisymmetry in the September tides and the March and September model compositions are significantly different. A differencing method was used to isolate the lunar tidal effects in the TIE-GCM and these were compared with lunar tidal analyses of ionospheric data. The model reproduces the broad features of the lunar tide in foF2 with phase changes around 7 degrees magnetic dip latitude during daytime. The model and data analysis both give variations of the amplitude and phase of the lunar tide with local time. Near the equator the variation of phase with local time changes with latitude as the equatorial anomaly develops during the day. Comparison between the model predictions and analyses of data at observatories at midlatitudes produced mixed results. Here the effects of the lunar components of both electrodynamic drifts and of neutral winds need to be taken into account. Several cases of day to night changes in the phase of the lunar tide in foF2 were noted. Large nighttime amplitudes of the lunar tide in hmF2, more than 4 km, seem to be due to in-phase action of the electrodynamic and neutral wind effects while during daytime they are out of phase. The lunar tide effect in the ratio of atomic oxygen to molecular nitrogen was estimated and found to be of relatively minor importance. Amplitudes of the lunar tide in foF2 may be measured at more than 0.4 MHz at some local times but the model values are less than this. Comparison was also made with ion drift measurements made by the San Marco D satellite.

- Emery, Roble, and 7 other university scientists used satellite and ground-based observations from November 2-11, 1993, as inputs to AMIE, and then used AMIE as input to the TIE-GCM. The November 1993 storm was an unusually strong storm associated with a recurring high speed stream of plasma velocity in the interplanetary medium in the declining phase of the solar cycle. Significant gravity waves with phase speeds of about 700 m/s caused by Joule heating were present in the upper thermosphere as perturbations to the neutral temperature and wind fields, especially on November 4.

The observed gravity waves in the meridional wind and in the height of the electron density peak at several southern hemisphere stations were generally reproduced by the model using the AMIE high latitude inputs. Both model and observed equatorward winds were enhanced during the peak of the storm at Millstone Hill and at Australian ionosonde stations. The observed neutral temperature at Millstone Hill increased about 400 K during the night on November 4, returning to normal on November 9, while the model increased 300 K the first night at that location but was still elevated on November 11. Enhanced westward winds were evident in the UARS WIND Imaging Interferometer (WINDII) data. The enhanced westward winds in the model were largest around 40 to 45 degrees magnetic latitude at night, and also tended to be largest in the longitudes containing the magnetic poles. The results showed that the TIEGCM using realistic AMIE auroral forcings were able to reproduce many of the observed time dependent features of this long-lived geomagnetic storm.

- The gravity wave parameterization scheme adapted from the NCAR Community Climate Model version 3.6 (CCM3) is further tested and tuned by Roble and Liu for both the TIME-GCM and the flux coupled TIME-GCM/CCM3 models. With this scheme, the TIME-GCM is able to produce wind and temperature structures that compare favorably with UARS satellite observations for both the solstice and the equinox cases. It is found that, to obtain agreement between the simulation and the observations, the gravity wave sources at the lower boundary (30 km) should be anisotropic, with dominant eastward components over westward and meridional components. For the coupled TIME-GCM/CCM3 model, the orographic gravity wave forcing has been incorporated in addition to the propagating wave components. The simulation results show that the orographic gravity wave forcing is dominant between the upper stratosphere and the middle mesosphere (40–70 km) during the winter season (especially in the northern hemisphere). Such forcing decelerates the otherwise very strong eastward winter jet in that region and replaces the previous Rayleigh friction assumption.

- Scott Palo (University of Colorado), Maura Hagan (HAO) and Roble used the TIME-GCM to understand the effects of the quasi-two-day wave (QTDW) on the middle atmosphere horizontal wind and temperature fields. A zonal wavenumber three perturbation with a period of 48 hours and a latitudinal structure identical to the (3,0) Rossby-gravity wave mode has been included at the lower boundary of the model. A response in the middle atmosphere horizontal wind fields is observed with a structure qualitatively similar to observations and other model results. Evidence for nonlinear interactions between the QTDW and the migrating tides is observed. This includes significant (40–50%) decreases in the amplitude of the migrating tides when the QTDW is present and the generation of wave components which can be tracked back to an interaction between the QTDW and the migrating tides. Clear evidence for the existence of a westward propagating zonal wavenumber six non-migrating diurnal tidal component which results from the nonlinear interaction between the QTDW and the migrating tides is also observed.

- Roble has suggested that forcings from the lower atmosphere are the likely the source of the day-to-day variability that has been observed in the upper atmosphere for years but has not been adequately described by upper atmosphere models. The source of this variability is weather systems and other disturbances generated in the troposphere that propagate upward into the upper mesosphere and lower thermosphere and produce considerable variability on horizontal scale-sizes of thousands of kilometers. These structures are similar to those observed by the WINDII and HRDI instruments onboard the UARS satellite. The structure of the diurnal tide calculated by the flux coupled models are similar to those observed by the HRDI and WINDII instruments with maximum amplitude occur in the spring equinox period and minimum tidal amplitudes at the solstice. The flux coupled tidal amplitudes, however, are about a factor of 2 lower than the observed tidal amplitudes. These simulations were done with the solar radiative and auroral forcings held constant throughout the period in order to examine the nature of the couplings between the lower and upper atmospheres. For the third year run realistic time-dependent solar radiative and auroral forcings will be introduced into the model and the couplings with solar and lower atmospheric generated variability will be examined.

- Michael Mendillo (Boston University), Henry Rishbeth (University of Southampton), and Roble have examined the variability of the ionospheric F-region peak electron density and peak heights in the flux coupled model simulations and compared them with the geomagnetic quiet time variation observed by ionosondes at various stations located around the world. They find that the variability in the model simulations is very similar but generally smaller (~75%) than the observed ionosonde variability. The seasonal variations are similar to the observations but the model predicted overall densities can at times be smaller that the observed values and this discrepancy they attribute to missing physics describing the interaction between the topside ionosphere and plasmasphere in the model. This boundary couplings will be improved for the next year simulation.

IMPACT/APPLICATION

The models we have developed are community models and they have been used by over 100 scientists and students over the past few years. Thus, the models are constantly being evaluated, upgraded and improved by the community feedback. We participate in PRIMER campaign studies, NSF Coupling and Energetics of Atmospheric Regions (CEDAR), Geospace Environmental Modeling (GEM), and Space Weather Initiative (SWI) programs. The models have been used for the NASA Space Physics Theory Program, the Atmosphere Explorer (AE), Dynamics Explorer (DE), Solar Mesosphere Explorer (SME), Upper Atmosphere Research Satellite (UARS), and the Global Geospace Study (ISTP/GGS) NASA satellite missions as well as U.S. Air Force and Navy satellite missions. We have also participated in the CRISTA and MAHRSI space shuttle experiments. We also participate in the NCAR Climate Systems Modeling effort in examining the couplings between the upper and lower atmospheres and in an attempt to understand the effects of the variable solar outputs on the coupled Earth system.

TRANSITIONS

There have been no transitions thus far with the contract. The models are being developed for eventual ONR and Space Weather studies.

RELATED PROJECTS

The numerical modeling effort is complemented by a data analysis and interpretation effort. Data from the following satellites have been analyzed and compared with model simulations:

- NASA DYNAMICS EXPLORER MISSION
- NASA UPPER ATMOSPHERE RESEARCH SATELLITE (UARS)
- NASA CRISTA AND MAHRSI EXPERIMENTS ONBOARD THE SPACE SHUTTLE

- NASA ISTP/GGS SATELLITE MISSION
- NSF CEDAR CAMPAIGNS
- NSF GEM CAMPAIGNS

PUBLICATIONS

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PRESENTATIONS IN FY1998

“Geomagnetic Activity Effects in Winds in the Lower Thermosphere” (A. D. Richmond, C. Lathuillere, B. A. Emery, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Gravity Wave Parameterization Applied to TIME-GCM for the Study of Middle and Upper Atmosphere Dynamics” (H. Liu, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Modeling the Effects of Diffuse Auroral Precipitation on the Upper Stratosphere and Mesosphere” (G. Crowley, R. Frahm, A. Ridley, D. Winningham, J. Sharber, R. Link, R. G. Roble, and J. M. Russell). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Imaging of Thermospheric Response to the July 13, 1982 Solar Proton Event” (D. P. Drob, R. R. Meier, D. J. Strickland, R. Cox, J. D. Craven, T. J. Immel, R. G. Roble, and A. C. Nickolas). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Thermospheric Neutral Response to the November 1993 Storm” (B. A. Emery, R. G. Roble, D. J. Knipp, C. Lathuillere, P. G. Richards, P. J. Wilkinson, M. J. Buonsanto, and D. P. Sipler). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Variations of Total Electron Content Geomagnetic Disturbances: A Model/Observation Comparison” (G. Lu, X. Pi, A. D. Richmond, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Solar Minimum Spectral Irradiance from the Soft X-rays to the FUV” (F. G. Eparvier, S. M. Bailey, T. N. Woods, G. J. Rottman, S. C. Solomom, G. M. Lawrence, R. G. Roble, O. R. White, J. Lean, and W. K. Tobisca). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“TEC Comparisons with the TING Model During the April WLS/UARC Campaign” (A. G. Burns, T. L. Killeen, W. Wang, A. Mannucci, X. Pi, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Mapping POLAR Auroral Images into the Thermosphere-Ionosphere Nested Grid (TING) Model” (W. Wang, Q. Wu, T. L. Killeen, A. G. Burns, L. A. Frank, J. P. Sigwarth, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“The Relevance of Proton Precipitation in the High Latitude Regions” (M. Galand, J. Lilensten, D. Lummerzheim, and R. G. Roble). Paper presented at the Fall AGU Meeting, San Francisco, CA, December 8-12, 1997.

“Effects of the Quasi-Two-Day Wave in the Mesosphere-Thermosphere-Ionosphere System” (S. E. Palo, R. G. Roble, and M. E. Hagan). Paper presented at the Spring AGU Meeting, Baltimore, MD, May 26-29, 1998.

"Geomagnetic Storm Effects on the Neutral Thermosphere at Solar Minimum" (A. G. Burns, W. Wang, T. L. Killeen, and R. G. Roble). Paper presented at the Spring AGU Meeting, Baltimore, MD, May 26-29, 1998.

"Particle Effects on the Middle Atmosphere Modeled Using the Parallelized TIME-GCM" (G. Crowley, A. Ridley, R. Link, D. Winningham, R. Frahm, J. Sharber, R. G. Roble, and A. D. Richmond). Paper presented at the Spring AGU Meeting, Baltimore, MD, May 26-29, 1998.

"Modeling of High-Latitude Thermosphere Joule Heating at High Spatial Temporal Resolution" (F. Li, T. L. Killeen, A. G. Burns, W. Wang, Q. Wu, R. G. Roble, L. A. Frank, and J. B. Sigwarth). Paper presented at the Spring AGU Meeting, Baltimore, MD, May 26-29, 1998.

"Ionospheric Variability Originating from Tropospheric and Stratospheric Sources" (M. Mendillo, H. Rishbeth, R. G. Roble, E. Damboise, and J. Wroten). Paper presented at the Spring AGU Meeting, Baltimore, MD, May 26-29, 1998.

"Ionization from Proton Aurora in the TIE-GCM" (M. Galand, R. G. Roble, and D. Lummerzheim). Paper presented at the 1998 CEDAR Workshop, Boulder, CO, June 8-12, 1998.

"Effects of the Quasi-Two-Day Wave in the Mesosphere-Thermosphere-Ionosphere System" (S. E. Palo, R. G. Roble, and M. E. Hagan). Paper presented at the 1998 CEDAR Workshop, Boulder, CO, June 8-12, 1998.

"Modelling of the Penetration of High-Latitude Electric-Fields to Low Latitudes for Non-Steady Conditions" (C. Peymirat, A. D. Richmond, and R. G. Roble). Paper presented at the 1998 CEDAR Workshop, Boulder, CO, June 8-12, 1998.

"Next Generation Models for Space Weather Specification and Forecasting" (G. Crowley, C. Freitas, A. Ridley, R. G. Roble, A. D. Richmond, D. Winningham, and R. Link). Paper presented at the 1998 CEDAR Workshop, Boulder, CO, June 8-12, 1998.

"The Response and Time Lags in the Neutral Thermosphere from Magnetospheric Forcing During the November 1993 Storm" (B. A. Emery, R. G. Roble, C. Lathuillere, D. J. Knipp, P. G. Richards, P. Wilkinson, M. Buonsanto, and D. Sipler). Paper presented at the GEM Conference, Snowmass, CO, June 15-19, 1998.

"A Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation Model" (C. Peymirat, A. D. Richmond, B. A. Emery, and R. G. Roble). Paper presented at the GEM Conference, Snowmass, CO, June 15-19, 1998.